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Powering In-pipe Wireless Sensors Using Flexible Piezoelectric Micro-generators

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Abstract: This paper presents a new piezoelectric energy harvester that generates sufficient energy to power wireless sensor nodes autonomously. Multiple PVDF-foils are layered alternately with electrode foils and wound to a spool. Due to induced turbulence inside standard flow pipes the piezoelectric foils are forced to oscillate converting kinetic energy into mechanical stress thus generating electrical charge. The new multilayer spool design tackles the common disadvantages of similar harvesters related to low piezoelectric coefficients of Polyvinylidenefluoride or brittleness of Lead-zirconate-titanate. Wind channel experiments to prove the feasibility of the concept result in a harvested output power of 0.54 µW at a wind velocity of 7 m/s. With efficient duty cycling of the sensor node 324 µWs of energy are available for data transmission. The presented harvester is proposed as a universal power supply for sensors inside pipe systems. All of the systems components are included inside the pipe allowing for a maintenance-free deployment of sensors in remote locations.

Keywords: autonomous sensor, flow harvester, PVDF-spool

Introduction

Driven by the need to constantly collect data about different parameters and processes for reasons of monitoring or optimization purposes, wireless sensor networks (WSNs) have been receiving increased attention in the past years. The advancement of technologies for data collection enabled the use of WSNs in a wide field of applications. Industrial processes, military operations, environmental and health monitoring are just a few of these application fields. The possibility to observe different physical parameters at a high resolution and in close proximity of the phenomenon has made WSNs an essential way to monitor or control different processes (Akyildiz et al. 2002). In order to fully benefit from WSNs, a dense deployment of sensor nodes is advantageous. Supplying the large amount of sensor nodes with sufficient energy using traditional power sources such as wiring them to a grid or equipping them with batteries limits their application in rough or isolated environments. Moreover, batteries have a negative impact on the operational life span of sensor nodes as they must be replaced after depletion. Furthermore, battery replacements are not always possible due to inaccessibility of the node. In many cases replacements are also accompanied by outages in the system to be monitored. Addressing these issues, a significant research effort has been directed towards finding alternative energy sources to supply wireless sensor nodes autonomously and avoid the need to replace dead batteries (Kim, Kim, and Kim 2011). Using different transduction principles such as thermoelectric (Snyder 2008), piezoelectric (Anton and Sodano 2007) or electromagnetic (Torah et al. 2008) to name a few, sufficient ambient energy is harvested and stored, enabling a maintenance-free sensor lifetime.

One field that would benefit from energy harvesting is in-depth monitoring of flow systems and water pipelines. Sensors to monitor flow conditions and fluid parameters are ideally placed inside distribution pipes. Currently, these sensors are supplied with power using electrical wires or batteries. Assuming the pipes are located within an electrical grid, penetrating the pipes to supply the sensors still presents one of the main causes of leakage due to sealing complications. Furthermore, replacing depleted batteries is complicated when pipes are unreachable (e. g., buried) and is accompanied by an economically unfavorable flow interruption. Placing an energy harvester (EH) inside the pipe that generates sufficient energy to power the sensor and enables wireless transmission is a reasonable solution.

The contribution of this paper is an alternative approach to harvest energy from flowing media such as air or water using flexible piezoelectric foils. The goal is to confirm the feasibility of this harvesting approach. The advantage of using piezoelectric foils is their scalability and low cost while being maintenance-free compared to commonly used electromagnetic transduction principles that involve rotating parts. Moreover, piezoelectric foils allow encapsulating the EH within the pipe to enable a

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universal power supply that is not tightly coupled with a specific sensor. This paper reports the results of several experiments conducted to determine the optimal configuration of polyvinylidene fluoride (PVDF) foils in a pipe with the goal of generating enough energy to power a wireless sensor node autonomously. First results show, that using PVDF-foils in a new configuration is a promising approach.

Related work is listed in the following section. Section "Design and Implementation" describes the working principle. The experimental approach is described in the section "Experimental Investigations" and its results are listed in section "Output Evaluation". The last section concludes the paper and gives an outlook on future work.

Related Work

Some EHs have been previously introduced that generate electrical energy from flowing media. Typical concepts to achieve this are the electromagnetic effect presented by Hoffmann et al. (2013), Torah et al. (2008), Ye and Soga (2011) or the piezoelectric effect used by Taylor et al. (2001), Pobering and Schwesinger (2003), Wang and Ko (2010), Kwon (2010), Liu et al. (2012). Electromagnetic harvesters require a relative movement of a magnet to a coil or vice versa and are difficult to scale down due to frictional losses (e. g., friction of rotational components) (Akaydin, Elvin, and Andreopoulos 2010). This makes the EHs unsuitable for applications inside standard water pipes. Piezoelectric harvesters on the other hand show a more promising scalability. Research shows that mainly two piezoelectrics are being used as active materials: lead-zirconate-titanate (PZT) (Kwon 2010; Liu et al. 2012) and PVDF (Taylor et al. 2001; Wang and Ko 2010). The latter has much lower piezoelectric coefficients than the former, which leads to small-scale harvesters generating relatively low power. Although this makes PZT more appealing as the active material, its brittleness and aging can have a negative impact on the operational life span. Also an application in fresh water distribution systems could be problematic due to health issues with lead containing materials. A new harvester is needed as a solution of this dilemma.

Design and Implementation

The developed harvester is based on the works of Taylor et al. (2001), Allen and Smits (2001) and Pobering and Schwesinger (2004). The idea is to use flow-induced turbulence in the wake of a bluff body to achieve mechanical stress in piezoelectric PVDF-foils. PVDF has excellent mechanical properties and chemical resistance making it suitable for in-pipe applications with no concern about aging, fatigue or health issues. In order to overcome the low output power traced back to the lower piezoelectric coefficients mentioned in "Introduction", a PVDF-spool is proposed. The piezoelectric foil is sandwiched between two aluminum layers and wound to a spool maximizing the active area. Figure 1 shows that this would lead to a contact between both electrodes resulting in a short circuit. A second PVDF layer is added to resolve this problem. Keeping in mind the right orientation of the polarized PVDF-foils, the active area is now doubled. Depending on the number of windings, a large active area can be achieved. Experimental investigations to determine the optimal number of windings are described in Harvester Configuration?.

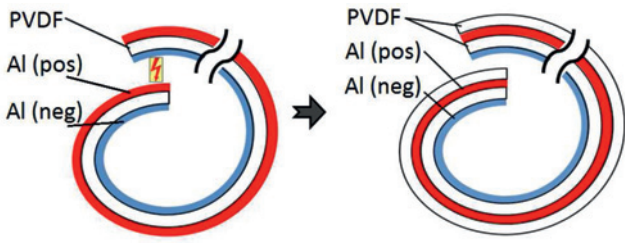

Figure 1: Short circuit prevention using two PVDF-foils (right) instead of one (left).

The PVDF-foil used in this configuration has a width and thickness of 12 mm and 25 µm, respectively. The 6 µm thick aluminum electrodes are only 8 mm wide. They are centrally layered alternating with the PVDF-foils and wound to form a spool. The length of the layers is determined by the diameter of the mandrel and the number of windings. It can be approximated by using the volume V of the foil in an unrolled form [1] and equating it with the volume of the wound foil on the mandrel [2]:

$$V = W^{\star}L^{\star}T, \tag{1}$$

$$V = W^{\star}\pi^{\star}\left(r_2^2 - r_1^2\right), \tag{2}$$

where W denotes the width of the foil, L its length and T its thickness. The radius of the mandrel is given by r_1 while r_2 denotes the radius of the most outer winding, which is dependent on n, the number of windings:

$$r_2 = n^{\star}T + r_1. \tag{3}$$

Inserting eq. [3] in [2] and eq. [2] in [1] then solving eq. [1] for L leads to:

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$$L = \frac{\pi^{\star}\left((n^{\star}T + r_1)^2 - r_1^2\right)}{T}. \quad (4)$$

In order to seal this configuration against liquid penetration, two layers of LDPE (low-density polyethylene) of 25 µm thickness are added as the most inner and most outer winding of the spool. These two layers are welded together forming a sealed ring-shaped harvester. LDPE is chosen due to its low young's modulus, which allows for an efficient energy transfer. In order to convert the kinetic energy of the flowing media into mechanical strain inside the piezoelectric layers, thus generating electric charge, a ring-shaped bluff body with an outer diameter of 30 mm and an inner diameter of 16 mm is placed upstream of the harvester to induce turbulence. The alternating (low-pressure) vortices cause the harvester to oscillate and undergo mechanical strain. Experiments to maximize this strain in order to maximize the harvester output are described in detail in Harvester Configuration?.

Experimental Investigations

To ensure system reliability and safeness, first tests to find the optimal harvester configuration inside the pipe were made with air as the flowing media. The harvester was tested in a 1″-pipe using a closed-loop wind channel from "ELV" (Uniwind). The different harvester configurations were operated at a constant wind speed of 7 m/s. The efficiency of the conversion of kinetic energy to mechanical stress inside the active layers was indicated by measuring the open-circuit voltage.

Harvester Configuration

Akaydin, Elvin, and Andreopoulos (2010) reported that "most of the losses occur during the conversion of flow's kinetic energy into mechanical/vibrational energy". This is why finding a suitable form and fixation method inside the pipe is crucial. By means of a live measurement while operating with the harvester form, three fixation methods (tested separately) showed promising outputs. The first form is similar to a flag or "eel" (Taylor et al. 2001; Allen and Smits 2001) with the harvester fixed to the pipe bottom with a screw and the free end oscillating with the flow. The other two variants are fixed with several screws in order to achieve a mechanical pre-stress. Figure 2 illustrates the different alternatives. One form looks like a boot fixed with three screws. The vortices

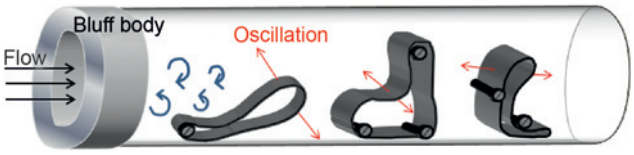

Figure 2: Initial three harvester shapes investigated: "eel"(left), boot (center) and L-shape (right).

induced by the bluff body cause one side of the harvester to bend, while the pre-stress inside the materials returns the layers to the first position. The last form has an L-shape, with the pre-stress causing the harvester to hold up against the flow, supported by a screw fixed upstream of the harvester. This form achieves a free vertical oscillating end.

First experiments show that the length of the harvester causes the free end to reach the top of the pipe-wall, restricting its oscillation. This is why a shorter harvester is investigated. The new harvester is wound on a mandrel with a diameter of 20 mm instead of 27 mm. In order to have a direct comparison, the number of windings was kept to four windings. The alternative winding process results in a stiffer harvester that allows for a new fixation inside the pipe. The harvester is now fixed in an "eel" shape, this time facing the flow. The pressure fluctuations and the harvester-stiffness cause a stable oscillation of the layers. Due to its promising result, the new configuration is used throughout the remaining experiments to determine the optimal position of the harvester behind the bluff body. The harvester was examined in the reversed "eel" form at different positions. The maximum and minimum distance to the bluff body, measured from the screw, were 5.5 cm and 2 cm, respectively. The results are shown in Table 1. In order to maximize the active area without exceeding a certain stiffness that could restrict the harvester's movement, the ideal number of windings had to be identified. Tests were made with a number of windings ranging from two to six.

Table 1: RMS-voltage of reversed "eel" measured at different positions from the bluff body.

EH position	2 cm	2.5 cm	3.5 cm	5.5 cm
RMS-voltage	1.2 V	1.4 V	1.1 V	0.8 V

Impedance Matching

After determining the optimal harvester configuration inside the pipe that maximizes the mechanical strain,

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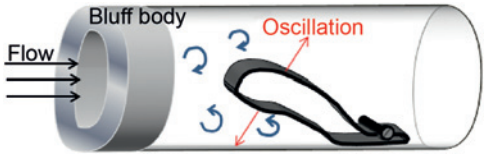

Figure 3: PVDF-spool fixed in the reversed "eel"-shape inside the pipe.

the harvester output is characterized with regard to the delivered energy. The goal is to deliver enough energy to enable the transmission of a sensor data package every 10 min. The energy required for such a duty cycle is about 200 µWs. The delivered energy by the flow harvester, is measured across a load and extrapolated to a 10 minute time frame to fit the application requirements. To deliver the maximum energy across a load, which is exactly 50 % of the total energy generated, the generator's impedance needs to be matched by the electrical load. This is done by fixing the harvester inside the pipe, allowing for a stable oscillation, while measuring the voltage drop across different electrical resistors. We tested loads ranging from 100 kΩ to 10 GΩ. The power and energy were then calculated using Ohm's law.

Output Evaluation

The measured voltage during the investigations indicates the efficiency of the conversion from kinetic flow energy to mechanical stress inside the active materials. Evaluating the voltage courses of the initial three harvester forms seen in Figure 4 reveals that the output is almost identical. The expected higher outputs using harvester shapes with material pre-stress is not confirmed. Although the L- and boot-shaped harvesters experience higher mechanical strains, the area free to oscillate is smaller compared to the "eel", which in terms decreases the efficiency.

The last form investigated is the reversed "eel". This configuration showed an increase in the output voltage by a factor of five. Due to the reversed orientation, the harvester undergoes greater forces, resulting in an oscillation with larger amplitudes and therefore increased mechanical stress. Achieving such a stable oscillation is only possible using a shorter harvester because of the increased stiffness that prevents the harvester from collapsing with the flow. The stiffness is controlled by the number of windings. Examining the harvester with different windings ranging from two to six, reveals that the

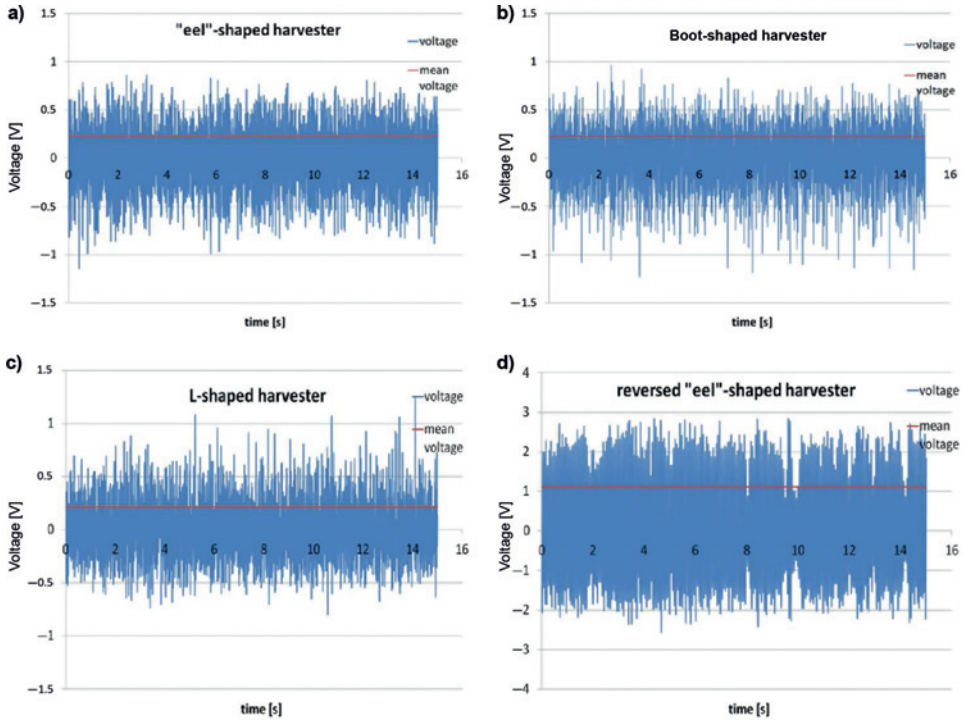

Figure 4: Voltage output of: a) "eel"-shaped harvester, b) boot-shaped harvester, c) L-shape harvester and d) reversed "eel"-shaped harvester.

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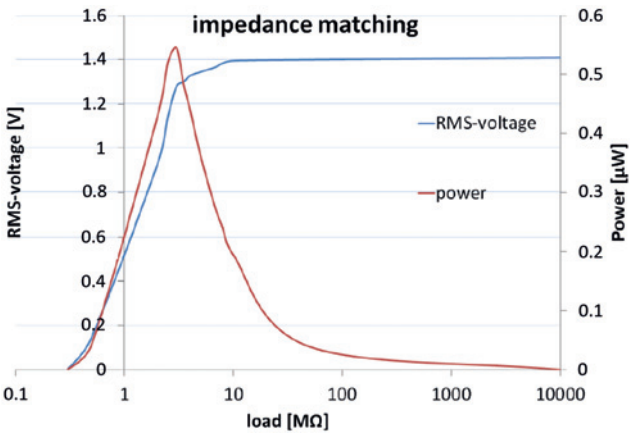

Figure 5: Impedance matching for the reversed "eel"-shaped harvester.

optimal number of windings is four. While harvesters with more than four windings are too stiff to oscillate, harvesters with less than four windings are too flexible, which results in an unstable oscillation or a collapse in the worst case. The position of the harvester also influences its output. Table 1 shows that the highest output is achieved at a distance of 2.5 cm from the bluff body. Figure 4 shows a comparison of the voltage output of the examined harvester forms. The voltage course of the reversed "eel" shown in Figure 4(d) is measured with four windings at the optimal position.

MΩ results in a power output of 0.54 µW. This output would provide an energy of 0.32 mWs for the application proposed in the section Impedance Matching?. This amount exceeds the minimum requirements and combined with efficient duty cycling of the sensor node is sufficient for wireless data transmission. However, there is a pressure drop accompanying this approach that is much higher than the current output and compromises the efficiency of the proposed system. Further investigations are required to optimize the setup and improve the efficiency.

Conclusion

An improved flow energy harvester has been developed, that tackles the disadvantages of similar systems. The piezoelectric effect in PVDF is used to convert energy from water flow inside standard pipes into electrical energy. The flexibility and mechanical robustness of this material together with its bio-compatibility (lead-free) make it a promising alternative to the PZT used in other energy harvesters. To overcome the low piezoelectric coefficients of PVDF, the thin foils are wound to a spool to maximize the active area and allow for a higher charge generation. The conversion efficiency of the harvester was tested using a wind channel. Tests showed, the fixation form of the spool inside the pipe is crucial for a high harvester output. Different forms were examined and promising results were achieved using an "eel"-shaped form, that is facing the flow and oscillating due to induced vortices. The load resistance was matched to the internal load of the generator in order to extract the maximum power. At 3 MΩ the harvester delivers a power of 0.54 µW. Depending on the desired application, this output power is sufficient to supply wireless sensor nodes with the help of efficient duty cycling.

Future work includes investigating the harvester in water instead of air and evaluating its output. It is expected that the higher kinetic energy of water flow, due to the higher density of the fluid, should lead to even more promising results for this EH. Guaranteeing the watertightness of the whole system is also part of the ongoing work. A final packaging that includes all of the system's components is to be designed. Figure 6 illustrates the system components inside the pipe. This will avoid the usual leakage problems accompanied by penetrating pipes in order to connect the components and allow for a maintenance-free deployment of sensors in remote locations.

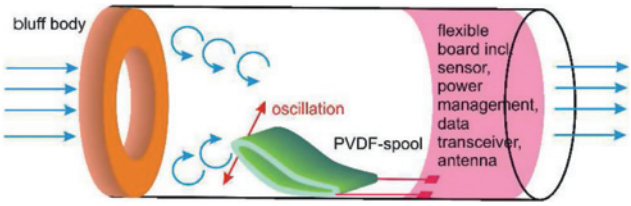

Figure 6: Concept of the proposed flow-harvester.

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References

Akaydin, H. D., N. Elvin, and Y. Andreopoulos. 2010. "Energy Harvesting From Highly Unsteady Fluid Flows Using Piezoelectric Materials." *Journal of Intelligent Material Systems and Structures* 21:1263–78.

Akyildiz, I. F., W. Su, Y. Sankarasubramaniam, and E. Cayirci. 2002. "Wireless Sensor Networks: A Survey." *Computer Networks* 38:393–422.

Allen, J., and A. Smits. 2001. "Energy Harvesting Eel." *Journal of Fluids and Structures* 15:629–40.

Anton, S. R., and H. A. Sodano. 2007. "A Review of Power Harvesting Using Piezoelectric Materials (2003–2006)." *Smart Materials and Structures* 16:R1.

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Hoffmann, D., A. Willmann, R. Göpfert, P. Becker, B. Folkmer, and Y. Manoli. 2013. "Energy Harvesting From Fluid Flow in Water Pipelines for Smart Metering Applications." *Journal of Physics: Conference Series*, IOP Publishing, 476:012104.

Kim, H. S., J.-H. Kim, and J. Kim. 2011. "A Review of Piezoelectric Energy Harvesting Based on Vibration." *International Journal of Precision Engineering and Manufacturing* 12:1129–41.

Kwon, S.-D. 2010. "A t-Shaped Piezoelectric Cantilever for Fluid Energy Harvesting." *Applied Physics Letters* 97:164102.

Liu, H., S. Zhang, R. Kathiresan, T. Kobayashi, and C. Lee. 2012. "Development of Piezoelectric Microcantilever Flow Sensor with Wind-Driven Energy Harvesting Capability." *Applied Physics Letters* 100:223905.

Pobering, S., and N. Schwesinger. 2003. "A New Micro Hydro Power Device" Poster Nanotech 2003 February 23-27 2003, San Francisco, Proceedings 2003 Vol. 1, S. 372–375.

Pobering, S., and N. Schwesinger. 2004. "A novel hydropower harvesting device", in *MEMS, NANO and Smart Systems, 2004. ICMENS 2004. Proceedings. 2004 International Conference on* IEEE, 480–5.

Snyder, G. J. 2008. "Small Thermoelectric Generators." *The Electrochemical Society Interface* 17:54.

Taylor, G. W., J. R. Burns, S. M. Kammann, W. B. Powers, and T. R. Wel. 2001. "The Energy Harvesting Eel: A Small Subsurface Ocean/River Power Generator." *IEEE Journal of Oceanic Engineering* 26:539–47.

Torah, R., P. Glynne-Jones, M. Tudor, T. O'Donnell, S. Roy, and S. Beeby. 2008. "Self-Powered Autonomous Wireless Sensor Node using Vibration Energy Harvesting." *Measurement Science and Technology* 19:125202.

Wang, D.-A., and H.-H. Ko. 2010. "Piezoelectric Energy Harvesting from Flow-Induced Vibration." *Journal of Micromechanics and Microengineering* 20:025019.

Ye, G., and K. Soga. 2011. "Energy Harvesting from Water Distribution Systems." *Journal of Energy Engineering* 138:7–17.

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